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Voltage Level and Wiring Weight for Aircraft Electrical Power Systems

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CONTENTS

ABSTRACT

A method for computing the wiring weight, conductor weight, and conductor losses as a function of system voltage is described for aircraft electrical power systems.

It is indicated that if phase voltage at the load is considered as system voltage for single-phase ground return systems and multiphase grounded neutral systems, then the number of wire conductors is equal to the number of phases. Hence, wiring weight, I^2R losses, and the number of conductors are directly proportional to the number of phases in a system and, for the same loads, the system voltage is inversely proportional to the number of phases. A 345-volt (three times the present 115-volt, three-phase voltage) single-phase system voltage would reduce the wiring weight, copper losses, and number of conductors to one-third their present value (on the three-phase ac system).

A significant point, or criterion, for optimum system voltage is reached at a system voltage where the system wiring weight divided by system wiring losses is a minimum.

PROBLEM STATUS

This is a final report on one phase of the problem. Work on other phases is continuing.

AUTHORIZATION

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VOLTAGE LEVEL AND WIRING WEIGHT FOR AIRCRAFT ELECTRICAL POWER SYSTEMS

NOMENCLATURE

A_c	Cross-sectional area of conductor.
I_o	Total current in a wire or system of wires; $I_o = 1$ per unit at voltage V_o.
I	Current (amperes).
I_1	Minimum current (amperes) in a given size wire.
I_2	Maximum specified current (amperes) for a given size wire.
i_1	Equal to I_1/V_s, the minimum current (amperes) at voltage V_s.
i_2	Equal to I_2/V_s, the maximum current (amperes) at voltage V_s.
$i_2 - i_1$	Equal to $(I_2 - I_1)/V_s$, the range of current at voltage V_s.
V_o	Initial or reference voltage, equal to 1 in the per unit system; $V_s = V_o$ at $s = 0$.
V_s	Voltage (per unit) at any step s; $V_s = (4/3)^s$.
s	Step value, an integer: 0, 1, 2, etc. Positive for increasing values of voltage and negative for decreasing values.
L_o	Unit length of wire (taken as 1,000 ft).
L_a	Average length of wire per ampere of current range; $L_a = L_o/(i_2 - i_1)$.
L	Length of wire (ft)
N	Assumed total number of loads carried by unit length of conductor L_o.
R	Resistance (ohms).
R_o	Resistance of 1,000 ft of wire L_o in reference gage at V_o; $R_o = 1$ in the per unit system.
R_s	Resistance (per unit) of 1,000 ft of wire, replacing that in reference gage at voltage V_s.
W_{wo}	Weight of 1,000 ft of wire in reference gage; $W_{wo} = 1$ in the per unit system.
W_{co}	Weight of conductor corresponding to wire weight W_{wo}; $W_{co} = 1$ in the per unit system. (See Table 3.)

W_{ws}	Weight of 1,000 ft of wire, replacing that in the reference gage at voltage V_s.
W_{cs}	Weight of conductor in the (per unit system) corresponding to wire weight W_{ws}.
W'_{ws}	Total wiring weight per phase of a system, or a number of systems combined, at voltage V_s.
W'_{cs}	Total conductor weight corresponding to wiring weight W'_{ws}.
W_{wg}	Weight of 1,000 ft of wire in principal gage at voltage V_s ; W_{wg} = W_{wg}/W_{wo} in the per unit system.
$W_{w(g+1)}$	Weight of 1,000 ft of wire in the wire size larger than the principal gage size.
$W_{w(g-1)}$	Weight of 1,000 ft of wire in the gage size smaller than the principal gage size, at voltage V_s. Usually small and may be zero.
W_{cg}, $W_{c(g+1)}$, $W_{c(g-1)}$	Symbols for conductor weight corresponding to W_{ws}, $W_{w(g+1)}$, and $W_{w(g-1)}$ for wire weight.
Principal gage size	At voltage V_o the principal gage is the reference gage, and at voltage V_s it is s gage sizes larger than the reference gage, when s is minus or the voltage is decreasing. When the voltage is increasing, s is positive and the principal gage is s sizes smaller than the reference gage size.
Reference gage size	The reference gage is the initial gage size at voltage V_o. Per unit values for weight, losses, current, and voltage are equal to unity for each 1,000 ft of wire length in this gage.
α	The fractional part of the total current range, of the total number of loads, or of the total length of wire in the wire size larger than the principal gage size at voltage V_s. Usually small and may be zero.
β	The fractional part of the total current range, of the total number of loads, or of the total length of wire in the principal gage size at voltage V_s. Usually large and may be equal to 1.0, as it always is at voltage V_o.
γ	The fractional part of the current range, of the total number of loads, or of the total length of wire in the wire size smaller than the principal gage size. Usually small and may be zero.

INTRODUCTION

The trend, historically, in all types of electrical power systems has been to increase the system voltage as the load and transmission distance increase. On land-based systems, the justification for higher system voltage is primarily based upon economic considerations (1).

Although economics is also a consideration in aircraft electrical systems, the immediate problem in aircraft manifests itself as an excessive weight of wire in the transmission system when the system voltage is too low. The ever-increasing power requirements on aircraft have led to successive increases in system voltage, starting with a 6-V dc system, then a 12-V dc system, and finally the presently used 28-V dc system. On some aircraft (2) a 120-V dc system has been used successfully. The greatest difficulty with the dc systems proved to be the excessive wear of the brushes on motors, especially at the higher altitudes, and at higher voltages.

The presently used 200/115-V, three-phase, 400-Hz system was initially accepted with great reluctance, even though it permitted the use of induction motors, and therefore eliminated the brush wear problem encountered on dc motors and offered a remedy for the excessive weight of transmission wiring on the larger aircraft. Because of the problems connected with the paralleling of ac generators, and the need for the development of utilization equipment and of lightweight constant-speed drives, the older 28-V dc system still has many advocates for its use, especially for the smaller and lighter aircraft.

The rapid advances in the technology of aircraft and aerospace vehicles that have occurred during recent years have given rise to a need to evaluate not only new methods of secondary power transmission and energy conversion, but also the need to examine again old methods that may now be more practical. The introduction of solid-state devices offers great advantages in aircraft electrical systems. With brushless generators already in use, and promising progress being made with brushless dc motors, the old objections to high-voltage direct-current systems seem to lose their validity. The advances in solid-state technology offer advantages to both ac and dc systems in the area of lightweight and efficient converters over a wide range of both input and output voltages. The electromechanical switches and controls used in the past are today being largely replaced by solid-state devices which are lighter, faster, and more reliable.

Because of these advances, it is timely to examine what advantages are to be gained by going to higher system voltages on future aircraft electrical power systems and to examine and compare advantages and disadvantages of various primary systems, both ac and dc. A recent report (3) examines a primary high-voltage dc system contrasted to the present 3-phase ac system and decides in favor of the former, recommending a dc system voltage of 230 V. Another recent paper (4) deals with design considerations of high-voltage dc power on aircraft. In the present report the goal is primarily to outline a method for the determination of system wire weight, conductor weight, and wiring I^2R losses as a function of system voltage for any primary electrical power system—multiphase, single-phase, or dc.

The general method of analysis used here is similar to that given in a previous report (5). Here, however, application is made to additional aircraft, and both increase and decrease of system voltage is considered. The magnitude of the voltage steps used has been changed so that at each voltage step, on the average, all loads in a particular gage size are carried by the next larger or smaller size wire, depending on voltage decrease or increase. In addition, the relationships among single-phase and multiphase systems with respect to system voltage, system wiring losses, and system wiring weight have been indicated.

Table 1
Nominal System Voltages and Allowable Voltage Drops
(from Table 2 of MIL-W-5088B(ASG))

Nominal System Voltage(V)	Maximum Allowable Voltage Drop (V)	
	Equipment Operation	
	Continuous	Intermittent
28	1	2
115	4	8
200	7	14

AIRCRAFT ELECTRIC POWER SYSTEMS

There are two primary electric power systems in general use on aircraft today. The nominal system voltage and allowable voltage drops for these systems, as given in MIL-W-5088B(ASG) Ref. (6), are shown in Table 1. The primary power system on all but the smallest aircraft is the three-phase 200/115-V, 400-Hz system. The requirements of utilization equipment on aircraft, in general, result in a need for both ac and dc power. Therefore, if the primary power supply is ac, a certain portion of this power must be converted to dc power, and conversely, when the main power supply is dc, a certain portion of this must be converted to ac. In addition, there are requirements, especially in electronic equipment, for both ac and dc power at various voltage levels. Whether the main power supply is ac or dc, conversion equipment is needed to meet the power requirements of the loads. Obviously, the use of conversion equipment is not desirable since it adds weight and increases power losses.

This study is concerned specifically with the dependence of wiring weight and I^2R wiring losses on change in the primary ac system voltage. Because of load requirements, as outlined above, not all the wiring on an aircraft will be affected when the voltage level of the primary power system is changed.

The total wiring weight on each of the three aircraft used in this study is shown under three headings in Table 2. Not only is this tabulation a convenience in analysis, but it also emphasizes that only a part of all the wiring on an aircraft is affected when the primary power system voltage level is changed. In Table 2, "dc system" refers to the wiring associated with the 28-V transformer-rectifier-battery system, and "electronics" refers to the weight of interconnecting wiring for electronic equipment or any other equipment operating at voltage levels other than that of the ac or dc systems. In this study it is assumed that only the wiring weight under the heading "three-phase, ac" is changed when the magnitude of the voltage or the number of phases for that system is changed.

RELATIONSHIP OF SINGLE-PHASE OR DC TO MULTIPHASE SYSTEMS

When phase voltage at the load, at rated load current, is considered as "system voltage" for both single- and multiphase systems (where a grounded neutral in the multiphase system and a ground return in the single-phase system are assumed), then the number of wire conductors is equal to the number of phases. If any one of these systems (single-phase or multiphase) is to supply the same loads at the same distances, with the same size wire, and at the same magnitude of current in each wire, then system voltage must be inversely proportional to the number of phases. Under these conditions, the relative total weights of wiring, for a few gage sizes, in a single-phase system at 345 V, a

Table 2
Systems Wire Weight for the Three Aircraft Considered

Aircraft	Wiring Weight (lb)		
	Three-phase AC System	DC System	Electronics
WF-2	167.9	167.6	82.5
F4J	340.9	89.6	66.1
EA6B	121.7	28.0	863.0

two-phase system, and a three-phase system all normalized to the value 1 at 345V, are shown in Fig. 1. In general the total weight of wiring, the total I^2R wiring losses, and the total number of wires are directly proportional to the number of phases when the system voltage is inversely proportional to the number of phases. Each system, therefore, obeys the rule for an ideal system of conductors, where the wiring weight and wiring I^2R losses are each inversely proportional to the system voltage. In a choice of systems, the one with the lowest wiring weight and lowest I^2R losses is the single-phase system, but it suffers the disadvantage of having the highest system voltage. In making a comparison between the three-phase system, on the aircraft considered here, and an equivalent single-phase system, the per unit voltage, of 345 V (three times the three-phase system voltage of 115 V) is the starting point which gives one-third the wiring weight, one-third the wiring losses, and one-third the number of conductors found in the three-phase system.

Results for single-phase ac, if considered as representative of a single-wire ground return dc system, would be on the safe side. That is, weight and losses for dc would be less than for ac since dc is necessarily at unity power factor, and current values would therefore be less for the same number of kilowatts. An additional advantage is that dc resistance is somewhat less than that for 400 Hz. A two-conductor dc system, with plus-or-minus with ground return, and a two-phase ac system (with the same qualifications as to power factor and ac resistance as outlined for single phase) could be considered as equivalent.

A relationship among the various systems has been indicated for the quantities of greatest interest, namely, system wiring weight, number of conductors, and system wiring losses. These relationships hold at a system voltage corresponding to the present system voltage, which is 115 V on the three-phase ac system. In addition, what is required is the relation of system wiring weight and losses to system voltage. This is more difficult than establishing relationships among different systems at a given value of system voltage and is the concern of the remainder of this study.

ASSUMPTIONS

The following five assumptions were made for this study:

1. It is assumed that the total length of wire in each gage size is uniformly and equally distributed over the current range for that gage, that is, from minimum to maximum current. An exception is made for the smallest size wire (#22) where it is assumed that the total length of wire is distributed linearly over the current range, increasing from zero, at zero current, to a maximum at 5 A (see Figs. 4 and 7).

2. It is assumed that on all present 115-V ac systems the number of load circuits that are voltage-drop limited is negligible. This is the equivalent of assuming that the maximum current for any gage size wire is the same as the minimum current for the next larger size wire.

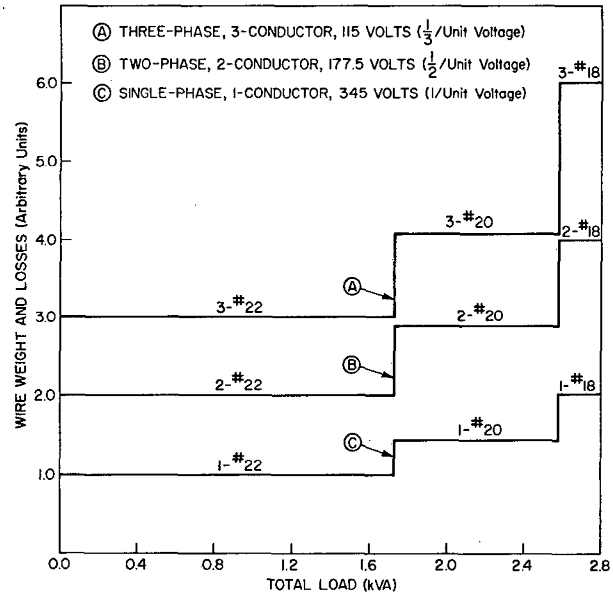

Fig. 1 - Relative wiring weight and I^2R losses as a function of total electrical load for three-, two-, and single-phase systems

3. It is assumed that the present specified values of voltage drop (1 and 4 V), for the 28-V and 115-V systems, respectively, determine and limit the minimum efficiency of transmission and the maximum voltage regulation, and that for a new standard system voltage the same ratio of voltage drop to system voltage would be maintained. In other words, it is assumed that it is the ratio of voltage drop to system voltage that is important and not the absolute value of voltage drop.

4. It is assumed that wiring for the ac system, installed on the three aircraft used in this study, conforms to the requirements of specifications MIL-W-5088B(ASG) and MIL-W-5086A (Ref. 7). It is further assumed in weight calculations that all wire is Type II.

5. It is assumed that at any new practical system voltage level considered, the present insulation used on 600-V wire would be adequate.

AIRCRAFT WIRE

The general requirements for the installation of aircraft wiring are given in MIL-W-5088B(ASG). This specification gives the maximum continuous—duty current for each gage size, for the conditions of single wire in free air, and for wires in conduit or bundles. The single wire in free air has the higher current rating.

Additional detail requirements for aircraft wire where the maximum conductor temperature does not exceed 105°C are given in MIL-W-5086A. A large proportion of the wire on the aircraft used in this study conforms to these specifications. For convenience and simplicity in the weight analysis, wire conforming to Type II, a medium-weight wire, has been used as representative of all the power wiring on the aircraft studied. Weight, resistance, etc., for this type wire are given in Table 3. The current ratings for bundled wires have been used exclusively because most wiring on aircraft today must conform to these lower current ratings. The bar plot of Fig. 2, a plot of relative wiring weight for each gage size, shows that wiring weight for wire sizes larger than No. 16 increases more than the current-carrying capacity.

Table 3
Typical Type II Wire Conforming to Specifications MIL-W-5086A and MIL-W-5088B(ASG)

Wire Size	Weight W_{wo} (lb/1000 ft)	Copper Weight W_{co} (lb/1000 ft)	Resist. R at 20°C (ohms/1000 ft)	Maximum Current I_2 (A)	Minimum Current I_1 (A)	Current Range I_2-I_1 (A)
AN-22	4.46	2.15	14.66	5.0	0	5.0
AN-20	6.45	3.45	9.19	7.5	5.0	2.5
AN-18	9.00	5.48	5.76	10.0	7.5	2.5
AN-16	11.30	7.13	4.42	13.0	10.0	3.0
AN-14	17.40	11.05	2.86	17.0	13.0	4.0
AN-12	24.70	17.70	1.78	23.0	17.0	6.0
AN-10	41.80	29.90	1.05	33.0	23.0	10.0
AN-8	67.50	48.50	0.65	46.0	33.0	13.0
AN-6	104.5	76.50	0.412	60.0	46.0	14.0
AN-4	157.0	122.0	0.258	80.0	60.0	20.0
AN-2	238.0	189.0	0.167	100.0	80.0	20.0

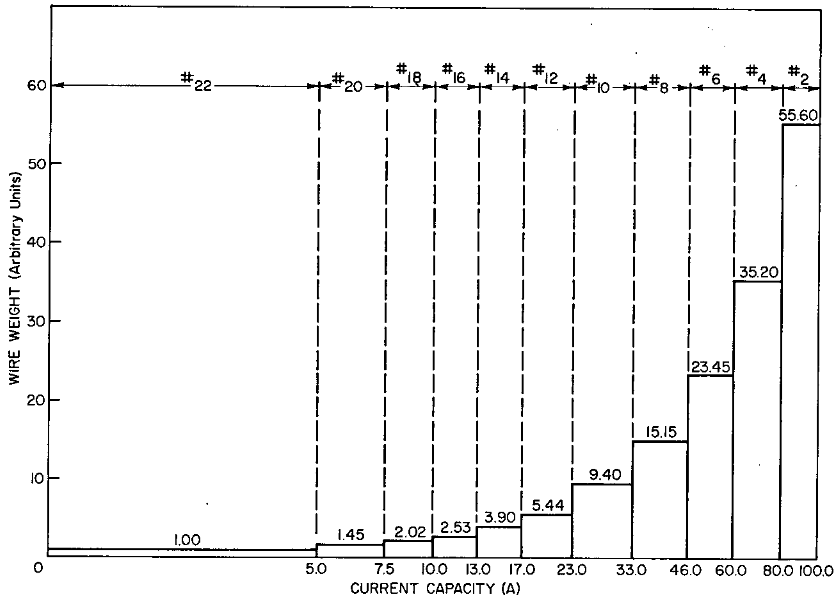

Fig. 2 - Relative wire weight as a function of current load for the gage size wires indicated

The maximum current rating of each gage size is approximately four-thirds the maximum current rating of the next smaller size when gage No. 18 is taken as a base. This relation is exact for No. 18 size, where the maximum current rating is 10 A and this is exactly 4/3 of 7.5 A, the maximum current of the next smaller size, gage No. 20. If this relation were exactly maintained throughout for all gage sizes, the calculation of change of wire weight with change in voltage level would be greatly simplified. To illustrate, suppose a number of loads at arbitrary distances from a common bus were supplied by No. 18 wire, and that the system voltage is V_0. Assume that the current to the smallest load is 7.5 A, and that to the largest load is 10 A. From Fig. 2 it can be seen that if all the loads carried by No. 18 wire are to be carried by No. 16 wire when the system voltage is lowered, then the total wiring weight will be increased by the ratio 2.53/2.02. If the initial voltage V_o is decreased to three-fourths its value, then the currents to the two loads must be increased to four-thirds their original values, or to 10 and 13-1/3 A for the smallest and largest load, respectively. Unfortunately, the maximum current specified for No. 16 wire is 13 A, and the 13-1/3 A load will have to be supplied by No. 14 wire, which is heavier than No. 16 wire.

This illustration in conjunction with the maximum and minimum values of current (I_2 and I_1) for each wire size, shown in Fig. 2, indicate that no single value of decreased system voltage will insure that all loads, carried by every gage size wire, will at a new decreased value of system voltage be carried by the adjoining larger size. Yet, when the system voltage is reduced by the factor 3/4, the major portion of all loads carried by each gage size wire, in a system, is transferred to the next larger size. It is therefore advantageous to use this factor 3/4 at each step in the reduction of system voltage, and its reciprocal 4/3 for increasing values of step voltage. Hence, the system voltage V_s at any step (increase or decrease) is given by

$$V_s = \left(\frac{4}{3}\right)^s \tag{1}$$

where s is the step (0, 1, 2, etc.) and is a positive integer for increasing values of system voltage, and negative for decreasing values. The resulting values of system voltage V_s, using Eq. (1), are in per unit, and its use is illustrated subsequently.

The concept of ampere-ft per unit weight of wire is basic and will prove useful in treating the electrical wiring weight problem.

The ampere-ft to any load is (see Nomenclature at front of report)

$$LI \tag{2}$$

and the weight of wire required is

$$\frac{LW_{wo}}{1000} . \tag{3}$$

The weight per ampere-ft is Eq. (2) divided by Eq. (1) or,

$$\text{weight/ampere-ft} = \frac{LW_{wo}}{1000} \times \frac{1}{LI} = \frac{W_{wo}}{1000I} . \tag{4}$$

The weight per 1000 ampere-ft is

$$\frac{W_{wo}}{I} . \tag{5}$$

Values for Eq. (5) are shown for all gage sizes from No. 22 to No. 2 in Fig. 3. This figure would be useful in weight determination if the designed current and length of wire of each and every load on an aircraft were known. Because the current to each load, assuming constant load, varies inversely as the system voltage, then that system voltage which gives the lowest average weight/ampere-ft for the whole system, if not perhaps the "optimum" system voltage, would at least be a significant signpost along the way. The

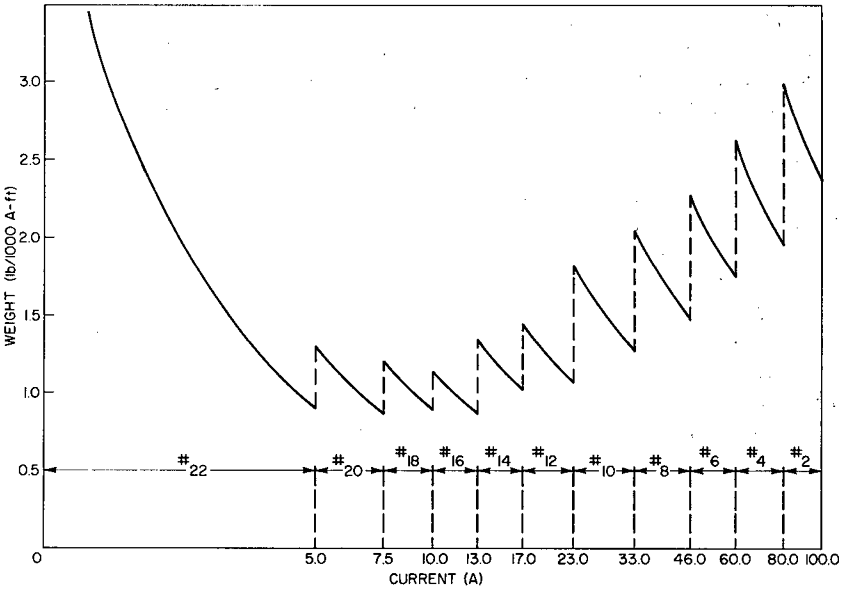

Fig. 3 - Weight per ampere-ft as a function of current load for the gage size wires indicated

difficulty of handling each and every load on a large aircraft would be a formidable task, so this approach will not be used. It will be observed (Fig. 3), however, that the lightest wires are Nos. 22, 20, 18, and 16 at values of current near their maximum current ratings. Therefore, it can be concluded that if the system voltage is at a value so that a very large portion of all the loads is carried by these minimum weight wires, then there is little to be gained by a further increase in system voltage. In general, an increase in system voltage will result in a decrease in system wiring weight and a decrease in system wiring losses. With an increase in ambient temperature, however, an increase in system voltage would be required to prevent an increase in wiring weight and wiring losses. A brief discussion of the effect of higher wire temperatures is given in the following section.

MAXIMUM WIRE TEMPERATURE, SYSTEM WIRING WEIGHT, AND SYSTEM VOLTAGE

Specifications MIL-W-5086A and MIL-W-7139A (Ref. 8) outline requirements for wire intended for use on aircraft at maximum wire temperatures of 100°C and 400°F (204°C), respectively. The maximum current-carrying capacity for wire covered by these specifications is the same and is given in MIL-W-5088B(ASG). The bundled current rating for wire, used in this study, is given in Table 3. The minimum weight of wire for higher temperature applications will in general be heavier than that required for the normal, 100°C, maximum wire temperature. Another drawback of wire operating at higher temperatures is that the maximum length of run within the permissible limits of maximum voltage drop (see Table 1) is shorter, for a given size wire at a given current, because of the increase in resistance. This leads to an increase in system wiring weight. For example, at a conductor temperature of 750°F, corresponding to the higher mach numbers, wire resistance is about 2.5 times that at room temperature (9). Based on resistance alone, it would take 2.5 times as much copper to carry the same current as at room temperature. The best way to avoid a large increase in wiring weight, because of an increase in temperature, is to increase the system voltage.

Minimum allowable efficiency of transmission and percent voltage drop are determined by the ratio of the maximum allowable voltage drop to the standard system voltage. An examination of Table 1 shows the maximum allowable voltage drops to be 3.57% and 3.48% of the nominal system voltage for the 28-V dc system and the 115-V ac system, corresponding to the 1- and 4-V drops, respectively. Therefore, the present maximum permissible voltage drop for both standard voltages expressed as a percent is K_n (approximately 3.5%). Hence K_nV_n is the voltage drop, in volts, for either system, where V_n is the system voltage in volts. A new standard voltage, for a higher maximum temperature, would have a maximum allowable voltage drop of K_tV_t where V_t is the voltage required to insure no increase in wiring weight at the higher wiring temperature (above the normal 100°C) and K_t is a fixed fraction, expressed in percent, and equal to the ratio of the maximum allowable voltage drop to the new nominal system voltage V_t. If the subscript n is used to denote present values applicable to present maximum temperatures, and the subscript t to denote values at other temperatures, then the ratio decreases for the maximum allowable voltage. For a given load and a given length and size of wire, the ratio is

$$\frac{I_nR_n}{I_tR_t} = \frac{K_nV_n}{K_tV_t} . \tag{6}$$

Multiplying each side of Eq. (5) by I_n/I_t, the ratio of the maximum allowable currents in any given size wire, the following equation is obtained:

$$\frac{I_n^2 R_n}{I_t^2 R_t} = \frac{K_n V_n I_n}{K_t V_t I_t} . \tag{7}$$

The volt-ampere requirements of a given load remain the same, without regard to wire temperature, and therefore $V_n I_n$ is equal to $V_t I_t$. The equation for the ratio of the maximum losses now becomes

$$\frac{I_n^2 R_n}{I_t^2 R_t} = \frac{K_n}{K_t} . \tag{8}$$

Hence, the maximum wire losses expressed as a percentage of power delivered to a load are equal to, and dependent on, the selection of the values of K_n and K_t. For the same efficiency of transmission, K_t must equal K_n. Solving Eq. (8) for I_t, the result is

$$I_t = I_n \sqrt{\frac{R_n K_t}{R_t K_n}} , \tag{9}$$

and since $V_n I_n$ is equal to $V_t I_t$, then

$$V_t = V_n \Big/ \sqrt{\frac{R_n K_t}{R_t K_n}} . \tag{10}$$

It is desirable when increasing the system voltage, so as to avoid increase in wiring weight, that there also be no decrease in transmission efficiency. From Eq. (8) it is apparent that, to obtain the same efficiency, K_t must be no greater than K_n. Hence, for no increase in system wiring weight and the same efficiency of transmission, with increased wire temperature the minimum system voltage will be that given by Eq. (10), with

K_t equal to K_n. For the condition that K_t equal to K_n, Eq. (10) becomes

$$V_t = V_n \sqrt{\frac{R_t}{R_n}} \; . \tag{11}$$

Normally, wire installed in aircraft is suitable for a maximum wire temperature of 100°C, and for the maximum current ratings and maximum voltage drop as indicated in MIL-W-5088B(ASG). This same specification, however, also specifies the same maximum current ratings and maximum voltage drop for wire covered under MIL-W-7139A, where the maximum wire temperature is given as 204°C. The wiring weight, system voltage, and maximum current rating could be maintained at the normal values if the expression under the radical in Eqs. (9) and (10) was made equal to unity. This is not possible since K_t must equal K_n for the same specified maximum voltage drop and the same transmission efficiency. Hence, for a given load where the maximum length of wire at a higher temperature and the maximum current are to be the same as that for the 100°C maximum wire temperature, a larger size wire would be required, assuming no change in system voltage, and this would result in an increase in weight. In addition, for shorter runs where maximum voltage drop is not involved, the loss per foot of the wire operating at higher temperature, and carrying the same load current as the same wire at lower temperature, is directly proportional to the resistance. Therefore, where there is a general increase in wire temperature, a system voltage increase to the value given for V_t in Eq. (11) will prevent an increase in weight and losses, but only if the maximum current rating for all gage sizes is derated by the amount V_n/V_t. In the case where there is to be no derating of maximum current (where I_n is equal to I_t) and K_n is equal to K_t, Eqs. (6) and (7) become

$$\frac{R_n}{R_t} = \frac{V_n}{V_t} \tag{12}$$

$$\frac{I_n^2 R_n}{I_n^2 R_t} = \frac{V_n I_n}{V_t I_n} \; . \tag{13}$$

In this case where there is no derating of maximum current, the required voltage for increases in wire temperature is proportional to the resistance, as indicated by Eq. (12). In the previous case, with derating of the maximum current, the required voltage, Eq. (11), is proportional to the square root of the resistance. Equation (13) shows that for the same size wire at higher temperature, both the load and loss are increased in the same proportion as the voltage. Hence, some loads carried initially at the lower temperature by a given size wire will, at the higher voltage, be carried by a smaller wire. So some reduction in system wiring weight will result. In the special case where all loads at the lower temperature were carried by the smallest size wire, there can be no reduction in weight and the current to each load would be decreased inversely as the voltage (or inversely as the resistance). There would then be an overall decrease in the losses equal to $1 - (V_n/V_t)$. In general, for a system there will be a smaller decrease in total losses than that for the smallest size wire, and also some decrease in total weight. However, the loss per foot for all conductors above the minimum size will be increased by the ratio R_t/R_n. With K_t always maintained equal to K_n, there is no decrease in efficiency of transmission for any load, and no increase in wiring weight.

If there is no derating in the maximum current-carrying capacity of high-temperature wires, as in the case for wire covered by MIL-W-5088B(ASG), then an increase in system voltage proportional to the increase in wire resistance is required to insure no increase in system wiring weight nor decrease in efficiency of transmission. Normally, on aircraft, only a few high-temperature wires are required, and an increase in system voltage would be justified only if there were other advantages in addition to maintaining the same weight of wiring for the high-temperature applications. The point emphasized here is that if there is a general increase in ambient temperature so that all wires in a system must operate at higher wire temperature, then the system voltage must be increased if an increase in weight and a decrease in transmission efficiency is to be avoided. In this study nearly all of the wire installed in the ac power system is for operation at a maximum wire temperature of 100°C, and therefore if this temperature is not exceeded, a saving in wiring weight and wiring losses can be anticipated with an increase in system voltage. The remainder of this report is concerned with the amount of these savings, under the assumption that no increase in maximum wire temperature is anticipated.

ANALYSIS OF WIRING WEIGHT

Rather than consider each individual load on an aircraft, it is much simpler when all the loads and all the wires in each gage size are considered as a single unit. Both the total current and total ampere-ft to all the loads carried initially by a particular gage size wire vary inversely as the voltage, if the distance (or length of wire) to each load and the magnitude of each load remain the same. The total length or weight of wire in each gage size for different aircraft is not the same, but it is convenient to consider a per unit wire length of 1000 ft. In Fig. 4, for a total length L_o of 1000 ft of wire in each gage, the average weight W_a of wire per ampere over the total current range I_2-I_1 for each gage is plotted. On the assumption that the weight distribution of wire (and length) is known over the the current range of each gage, it is possible to determine weight change in a whole system of wires, as a function of system voltage, by treating each gage size as a unit.

As an illustration consider gage No. 20 wire. The maximum and minimum currents I_2 and I_1 for this gage are shown in Fig. 5 at 1 per unit voltage. The curves i_2 and i_1 show the variation of the initial currents I_2 and I_1 with change in system voltage. The curves of maximum and minimum current are inversely proportional to the system voltage. Each step change in system voltage $V_s = (4/3)^s$ (Table 4) has been selected so that the major portion of the wire (βL_o) and loads carried by any gage size will be carried by the next larger or smaller size wire, called the principal gage, at each step. For example, starting with $V_s = 1$ per unit (that is, $s = 0$) assume that all 1000 ft of wire is in gage No. 20 (see Fig. 5) and that the wire weight and length distribution over the current range I_2-I_1 is uniform as shown in Fig. 6. At the next step, $s = -1$ (for a decrease in system voltage), $V_{-1} = 0.75$ per unit (see Table 4), and the current range i_2-i_1 is 3.33 A.

Since the distances to all the loads initially supplied by the wire in gage No. 20 do not change when the system voltage changes, then the 1000 ft of wire length initially required in gage No. 20 is still required when the voltage is reduced to 0.75 per unit (P.U.). This wire length is distributed, as initially (Fig. 6), uniformly over the new current range (i_2-i_1 or 10-6.67 A. In Fig. 5, it can be observed that this current range spans the complete range of gage No. 18 wire (7.5 to 10 A) and also 7.5-6.67 A in the current range of gage No. 20 (smaller wire size). Hence, at the voltage 0.75 P.U., 7.5-6.67/3.33 = 0.25 = γ of the total current range is in gage No. 20, and the remainder 10-7.5/3.33 = 0.75 = β is in gage No. 18 (principal gage). As the length of wire is constant over the current range, the fractional length (α, β, or γ) of wire in each gage is equal to the fractional part of the current range in that gage (see Table 4). Now if the weights of each of the fractional lengths of wire (β and γ) in the two gage sizes Nos. 18 and 20 are computed and the sum of these weights divided by the weight of the initial 1000 ft of wire in gage No. 20, the per unit weight or relative weight W_{ws} as a function of system voltage can be determined. Values of α, β, and γ, multiplied by 1000, for various values of voltage are given in Table 4 and are determined as illustrated above for 0.75 P.U. voltage. Of course, at 1.00 P.U. voltage all the wire is in gage No. 20, so β is equal to 1.00 and α and γ are zero. In general, the relative weight W_{ws} of wiring or wiring weight factor at any voltage is given by the expression (for explanation of symbols see nomenclature)and

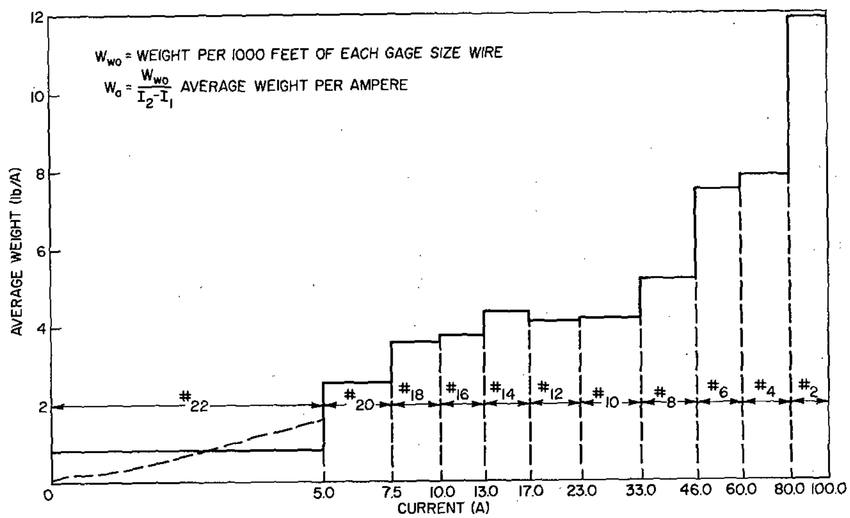

Fig. 4 - Average weight W_a per ampere of current range for the gage size indicated

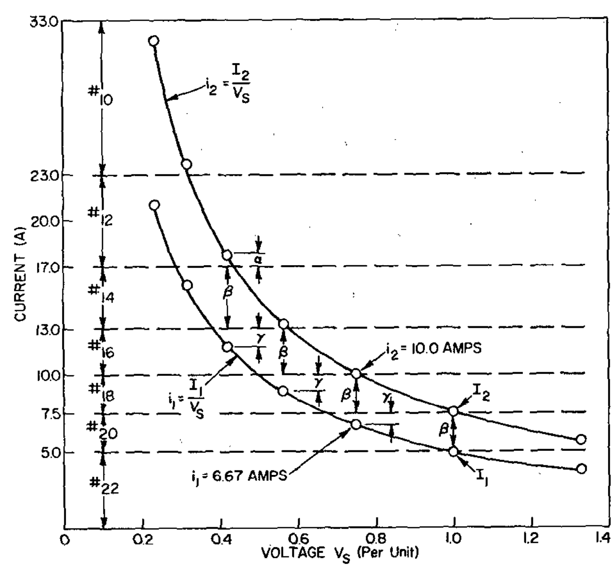

Fig. 5 - Variation of maximum and minimum currents (I_1 and I_2), initially carried by No. 20 gage wire, as a function of system voltage for the gage size wires indicated

Table 4
Variation of Maximum i_2 and Minimum i_1 Currents in 20 Gage Wire, and Replacement of Initial 1000 ft Wire with Change in System Voltage

Voltage Step	Voltage $V_s = (4/3)^s$ (per unit)	$i_1 = I_1/V_s$ (A)	$i_2 = I_2/V_s$ (A)	Current Range i_2-i_1 (A)	Principal Gage	Feet of Wire in Princ. Gage $\beta \times 1000$	Feet of Wire in Smaller size Gage $\gamma \times 1000$	Feet of Wire in Larger size Gage $\alpha \times 1000$
1	1.333	3.75	5.62	1.87	22	667	0	333
0	1.000	5.00	7.50	2.50	20	1000	0	0
-1	0.750	6.67	10.00	3.33	18	750	250	0
-2	0.562	8.90	13.33	4.45	16	674	247	79
-3	0.422	11.85	17.80	5.95	14	673	193	134
-4	0.317	15.80	23.70	7.90	12	760	151	89
-5	0.237	21.1	31.60	10.55	10	820	180	—

$$W_{ws} = \alpha \frac{W_{w(g-1)}}{W_{wo}} + \beta \frac{W_{wg}}{W_{wo}} + \gamma \frac{W_{w(g-1)}}{W_{wo}} . \qquad (14)$$

The lengths of wire in each gage size at a number of different voltage values are given in Table 4; the values of weight factor W_{ws} for these voltages are then obtained by use of the above equation and are listed in Table 5.

Figure 6 also illustrates, as does Fig. 5, the varying current range i_2-i_1 as the system voltage changes. Figure 6, however, emphasizes that the average length L_a of wire per ampere of current range must change as the current range changes. The total area over the current range for each voltage step in Fig. 6 remains constant and is proportional to the 1000 ft of wire initially in gage No. 20 at 1 P.U. voltage. In general the current range of any gage wire will, with a change in system voltage, span a fractional part of the current range of two or more gages, and because of this, to determine wire weight, the distribution of wire over the current range of the gage size considered at V_o must be known or assumed. The voltage steps have been chosen so that on the average all the wire in any gage will at each voltage step be replaced by the same length of wire in the next lower or higher gage size. If the maximum currents specified for each wire size conformed to the same relation as the voltage steps chosen, wire weight could easily be obtained with a change in system voltage and without the need to assume or know the wire distribution over the current range for each gage size. The weight and length of wire over the current range at 1 P.U. voltage for all gage sizes has been assumed as constant and equal to the average value. However, in the case of the smallest size wire No. 22, it did not appear probable that there would be as many loads near zero current as there would be at the maximum current for this size wire. Hence, the distribution of wire weight and length, from 0 to 5 A, was assumed to be linear and directly proportional to the current (see broken line on Fig. 4). No assumption for the distribution of wire in gage No. 22 is necessary for increasing values of system voltage since the weight of wiring for all loads supplied by this wire cannot change, although the current change, as for all other loads, is inversely proportional as the voltage.

If the same procedure is followed for all gage sizes, as has been outlined for gage No. 20, in going from 1.00 to 0.75 P.U. voltage, then a set of numbers W_{ws}, called wire weight factors and corresponding to the same voltage steps (or additional voltage steps) as used for No. 20 wire, may be obtained. These wire weight factors, corresponding to the voltages at each step and expressed in per unit, will, when multiplied by the initial

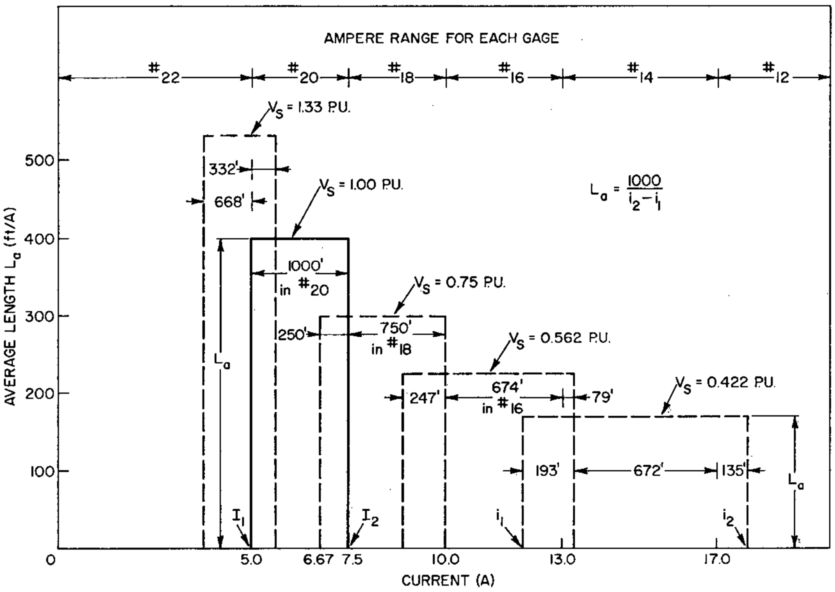

Fig. 6 - Average length of wire L_a per ampere of current as a function of current. Data obtained on 1000 ft of wire, initially No. 20 gage, at various system voltages.

Table 5
Relative Weight W_{ws} of 1000 ft of Replacement Wire (Initially No. 20 Gage) with Change in System Voltage

Voltage Step s	Voltage (Per Unit) V_s	Component Weights for Gage Sizes Indicated							Weight Factors W_{ws}
		22	20	18	16	14	12	10	
1	1.33	0.462	0.333						0.80
0	1.00		1.000						1.00
-1	0.75		0.250	1.050					1.30
-2	0.562			0.350	1.190	0.200			1.74
-3	0.421				0.338	1.820	0.576		2.67
-4	0.317					0.40	2.92	0.57	3.89
-5	0.237						0.69	5.31	6.00

weight of wire in each gage, give the resulting weight corresponding to each value of voltage.

A complete listing of wire weight factors for the most commonly used gage sizes, and for both increasing and decreasing values of voltage, is given in Table 6. If the weight or length of wiring in each gage size is known for one or more aircraft, then when this weight is multiplied by the corresponding weight factor in Table 6 the computed wiring weight corresponding to the new system voltage is obtained. Of course to obtain the total wiring weight in a given system at a particular voltage V_s, the computed wire weights for all gages, in the system considered, must be added.

Table 6
Wire Weight Factors W_{ws}

Voltage V_s (Per Unit)	W_{ws} for Gage Sizes Indicated										
	2	4	6	8	10	12	14	16	18	20	22
0.237				6.15	6.20	8.58	8.10	8.25	7.11	6.00	3.75
0.316			4.05	4.09	5.15	5.63	5.18	5.63	4.64	3.89	2.60
0.422		2.64	2.67	3.32	3.47	3.73	3.53	3.70	2.97	2.67	1.86
0.562	1.66	1.75	2.22	2.37	2.25	2.47	2.40	2.22	2.08	1.74	1.47
0.750	1.10	1.47	1.50	1.54	1.51	1.61	1.42	1.59	1.32	1.30	1.2
1.000	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1.333	0.66	0.65	0.65	0.68	0.69	0.71	0.64	0.80	0.72	0.80	1.00
1.780	0.42	0.44	0.42	0.47	0.46	0.45	0.51	0.57	0.60	0.69	1.00
2.370	0.28	0.27	0.30	0.31	0.33	0.35	0.37	0.46	0.50	0.69	1.00
3.160	0.18	0.20	0.20	0.20	0.22	0.26	0.29	0.39	0.50	0.69	1.00
4.220	0.11	0.13	0.14	0.14	0.16	0.21	0.26	0.39	0.50	0.69	1.00

ANALYSIS OF COPPER WEIGHT AND COPPER LOSSES

In Table 3 the copper weight per 1000 ft in each gage size wire is given, and a table of copper weight factors can be derived in a manner analogous to that used to obtain the wire weight factors (see previous section). The variation of copper weight as a function of system voltage is important for two reasons. First, in the attempt to determine an "optimum" system voltage, the copper weight may be more significant than the wire weight. Among different manufacturers of the same gage and type of wire there can be considerable differences in wire weight, although all wires conform to the same specifications. The differences are primarily due to differences in insulation weight. Differences in conductor (copper) weight, even for different types of wire and for different temperature applications, among different manufacturers will generally be negligibly small. So if the insulation and outer protective covering of wire is considered as a necessary weight penalty that indeed plays no part in conducting energy to the load, then the conductor may be the more important consideration. The second and more important reason for determining the weight of copper at each voltage step is, as will now be shown, that a relationship exists between the total weight of copper in a system at any voltage and the I^2R losses at that voltage.

If a phase load is supplied by a wire of length L, resistance R, and conductor weight W_c (ground return or grounded neutral is assumed), then the following expressions can be formulated:

$$R = \frac{\rho L}{A_c} \tag{15}$$

$$W_c = wLA_c . \tag{16}$$

The symbols ρ, w, and A_c are the resistivity, weight per unit volume, and cross section of conductor, respectively. The product of Eqs. (15) and (16) gives the relation

$$W_c R = \rho w L^2 \tag{17}$$

Equation (17) is always valid for any gage size single conductor of uniform cross section, and if the length L is constant, then the wire resistance for any size wire is equal to a constant divided by the weight of conductor. In per unit (i.e., normalized) the resistance is the reciprocal of the conductor weight.

In this analysis, for the sake of convenience and simplicity it is desirable to treat all conductors, in each gage, as a single conductor so that Eq. (17) may be used to determine the resistance of all conductors in a particular gage size. In the preceeding section a general formula for wire weight at any voltage V_s was derived. The corresponding formula for conductor weight, or conductor weight factor, is

$$W_{cs} = \alpha \frac{W_{c(g+1)}}{W_{co}} + \beta \frac{W_{cg}}{W_{co}} + \gamma \frac{W_{c(g-1)}}{W_{co}} . \tag{18}$$

Conductor weight factors W_{cs} are determined in a manner similar to that for the wire weight factors and are given in Table 7.

The resistance of 1000 ft of wire in any gage size is given in Table 3, and Eq. (14) indicates that the resistance of a fixed length L of conductor is inversely proportional to its weight. The resistance of 1000 ft of conductor, when distributed among different gage sizes, as indicated in the conductor weight equation above is not proportional to the reciprocal of the total weight W_{cs}, but to the sum of the reciprocal weights in each gage size. Hence, in general, the resistance of 1000 ft of conductor at any voltage is

$$R_s = \alpha \frac{W_{co}}{W_{c(g+1)}} + \beta \frac{W_{co}}{W_{cg}} + \gamma \frac{W_{co}}{W_{c(g-1)}} \tag{19}$$

Since it is assumed that all 1000 ft of wire is distributed equally and uniformally over the current range, then there are a total of N equal lengths of wire, and Eq. (19) indicates that αN lengths have a resistance of $W_{co}/NW_{c(g+1)}$ each. Similarly, the ratios following β and γ in Eq. (19), when divided by N, are the resistance of each length of wire in the remaining two groups. The magnitude of a load is not affected by change in system voltage, and the current (per unit) to each load is therefore $1/V_s$. Hence, the wire I^2R loss to any load is R/V_s^2. If R_α, R_β, and R_γ is the resistance of each wire in the groups αN, βN, and γN of Eq. (19), then the total loss of all the wires is

$$\frac{R_s}{V_s^2} = \alpha N \frac{R_\alpha}{V_s^2} + \beta N \frac{R_\beta}{V_s^2} + \gamma N \frac{R_\gamma}{V_s^2} . \tag{20}$$

Equation (20) is Eq. (19) with both sides divided by V_s^2. Since R_s is the series resistance of all the N conductors, which are in parallel and whose total length is a 1000 ft, Eq. (20) indicates that R_s/V_s^2 is equal to the total losses in all the N wires connected in parallel. Only when α and γ are zero is R_s equal to the reciprocal of the total conductor weight.

Loss factors R_s/V_s^2 corresponding to the voltages in Tables 6 and 7 for wire weight factors and conductor weight factors are given in Table 8.

APPLICATION OF ANALYSIS TO AIRCRAFT SYSTEMS

Wire weight factors W_{ws}, copper weight factors W_{cs}, and copper loss factors have been determined for various values of voltage V_s above and below a reference, or per unit,

Table 7
Copper Weight Factors W_{cs}

Voltage V_s (Per Unit)	W_{cs} for Gage Sizes Indicated										
	2	4	6	8	10	12	14	16	18	20	22
0.237				6.78	6.58	9.40	9.80	9.55	8.40	8.08	5.18
0.316			4.35	4.35	5.64	6.05	5.95	6.43	5.46	5.18	3.33
0.422		2.68	2.80	3.60	3.73	3.68	3.98	4.20	3.50	3.26	2.27
0.562	1.06	1.71	2.34	2.58	2.32	2.47	2.71	2.53	2.23	2.04	1.68
0.750	1.21	1.48	1.60	1.58	1.52	1.66	1.60	1.63	1.37	1.45	1.26
1.000	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1.333	0.65	0.61	0.63	0.68	0.69	0.63	0.63	0.77	0.63	0.75	1.00
1.780	0.39	0.40	0.41	0.47	0.43	0.39	0.48	0.48	0.50	0.62	1.00
2.370	0.26	0.26	0.29	0.29	0.26	0.29	0.31	0.37	0.39	0.62	1.00
3.160	0.16	0.18	0.18	0.18	0.19	0.19	0.23	0.30	0.39	0.62	1.00
4.220	0.10	0.11	0.11	0.12	0.13	0.15	0.20	0.30	0.39	0.62	1.00

Table 8
Copper Loss Factors R_s/V_s^2

Voltage V_s (Per Unit)	Loss Factors (per unit per pound) for Gage Sizes Indicated										
	2	4	6	8	10	12	14	16	18	20	22
0.237				2.74	2.85	1.96	1.90	1.92	2.17	2.30	4.08
0.316			2.39	2.44	1.83	1.72	1.77	1.60	1.83	2.04	3.93
0.422		2.20	2.08	1.59	1.57	1.58	1.47	1.34	1.66	1.86	2.95
0.562	2.01	1.94	1.36	1.26	1.44	1.32	1.17	1.26	1.46	1.63	2.24
0.750	1.78	1.22	1.12	1.17	1.22	1.08	1.11	1.11	1.31	1.29	1.49
1.000	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1.333	0.87	0.93	0.89	0.85	0.85	0.91	0.89	0.73	0.90	0.79	0.562
1.780	0.82	0.79	0.78	0.73	0.77	0.82	0.67	0.66	0.67	0.51	0.316
2.370	0.70	0.71	0.63	0.65	0.70	0.62	0.57	0.51	0.45	0.29	0.178
3.160	0.64	0.59	0.58	0.59	0.55	0.52	0.46	0.33	0.26	0.16	0.100
4.220	0.57	0.52	0.52	0.46	0.47	0.41	0.29	0.19	0.14	0.09	0.056

voltage V_o. These various factors have been computed from the wire data given in Table 3. To compute the variation of system wiring weight, system copper weight, and system losses with projected changes in system voltage, for one or more given aircraft, the weight of wiring in each gage size must first be known. The corresponding weight of copper in each gage size, if not known, may then be obtained from the data in Table 3. This then is the initial weight of wire and the initial weight of copper required at the

Table 9
Wire Weight in Each Gage Size for Three-Phase, 115-V, AC Aircraft Systems

Wire Gage	Wire Weight (lb) for Aircraft Indicated			Total Weight Per Gage (lb)
	WF-2	F4J	EA6B	
8	4.48	12.90	18.96	36.34
10	1.43	28.10	16.03	45.56
12	11.30	4.35	8.53	24.18
14	5.70	2.46	0.86	9.02
16	34.00	46.40	11.06	91.46
18	10.80	38.70	8.88	58.38
20	76.80	129.00	41.09	246.89
22	23.40	79.00	16.34	111.74
Total(lb)	167.91	340.91	121.75	630.57

voltage V_o in the system considered. The weights or losses in each gage, at other voltages V_s, are obtained by multiplying the initial weight in each gage by the weight factors or loss factors corresponding to the voltages V_s. The sum of the weights in all gage size wires used in a system gives the total weight. The weights and losses are computed on a per phase basis, so that the results are directly applicable to a single-phase or dc system. Table 9 gives the total weight of wire in each gage for the three aircraft used in this study. Table 10 shows the per phase wire weight and copper weight in each gage for all three aircraft combined. These values of weight in each gage are multiplied by the appropriate weight factors and loss factors given in Tables 6-8 and the corresponding results are presented in Tables 11-13.

Figure 7 is a plot of phase wiring weight, taken from actual aircraft data presented in Table 10, which indicates that a very large percentage of wiring weight is in the smaller size wires, and therefore that little can be gained by increasing the present system voltage on the three-phase ac system.

Comparisons of the present three-phase wiring weight and copper weight with corresponding single-phase values as a function of system voltage are shown in Figs. 8 and 9, respectively. The crossover points of 164 V and 232 V indicate points of system voltage where wiring weight and copper weight in both systems (that is, single-phase and three-phase) are the same. Below these values of system voltage three-phase is better; above these values single-phase or dc is better. Data for plotting these curves has been taken from Tables 11 and 12. The per unit voltage is taken as 345 V and the per unit weight is the total weight per phase as indicated in Tables 11 and 12.

Table 13 shows the variation per phase of all the losses, and in this table the per unit voltage is also 345 V. The total losses for three phase would, of course, be three times the values shown in the table, and system voltage for three-phase would be one-third the corresponding voltage values.

Table 14 is a summary of systems wiring weight, copper weight, and systems losses taken from Tables 11-13, respectively. Since the total ampere-ft for a load or any system of loads varies inversely as the system voltage, the average wiring weight per ampere-ft

Table 10
Per Phase Wire Weight and Copper Weight in Each Gage Size for the WF-2, F4J, and EA6B Aircraft Combined

Quantities	Per Phase Weight for the Gage Sizes Indicated							
	8	10	12	14	16	18	20	22
Three-Phase Wire Weight(lb)	36.34	45.56	28.18	9.02	91.46	58.38	246.89	118.74
Per Phase Wire Weight(lb)	12.11	15.19	8.06	3.01	30.49	19.46	82.30	39.58
Per Phase Copper Weight(lb)	8.77	10.85	5.78	1.91	19.25	11.85	43.80	19.10
Per Phase Wire Weight Per Ampere(lb/A) (See Fig. 7)	0.93	1.52	1.34	0.75	10.16	7.80	32.90	7.92

Table 11
Variation of Phase Wiring Weight with System Voltage for AC Systems on the WF-2, F4J, and EA6B Aircraft Combined

System Voltage V_s (Per Unit)	Resulting Wire Weight (lb) for the Gage Sizes Indicated								Total Weight	
	8	10	12	14	16	18	20	22	(lb)	(Per Unit)
0.237	74.5	94.0	69.0	24.4	252.0	139.0	494.0	149.0	12,959	6.17
0.316	49.5	78.2	45.3	15.6	172.0	90.5	320.0	103.0	874	4.16
0.422	40.2	52.7	30.0	10.6	113.0	58.0	220.0	73.7	598	2.85
0.562	28.6	34.2	19.9	7.2	67.7	40.6	143.0	58.3	400	1.90
0.750	18.7	22.9	13.0	4.3	48.5	25.8	107.0	47.5	288	1.37
1.000	12.1	15.2	8.1	3.0	30.5	19.5	82.3	39.6	210	1.00
1.33	8.2	10.5	5.8	1.9	24.4	14.0	66.7	39.6	171	0.81
1.78	5.7	7.0	3.6	1.5	17.7	11.7	57.5	39.6	144	0.69
2.37	3.8	5.0	2.8	1.1	14.0	9.8	57.5	39.6	134	0.64
3.16	2.4	3.3	2.1	0.9	11.9	9.8	57.5	39.6	128	0.61
4.22	1.7	2.4	1.7	0.8	11.9	9.8	57.5	39.6	125	0.60

Table 12
Variation of Phase Copper Weight with System Voltage for AC Systems on the WF-2, F4J, and EA6B Aircraft Combined

System Voltage V_s (Per Unit)	Resulting Copper Weight (lb) for the Gage Sizes Indicated								Total Weight	
	8	10	12	14	16	18	20	22	(lb)	(Per Unit)
0.237	59.46	77.8	54.3	18.7	184	99.5	353	99.0	945.8	7.797
0.316	38.10	61.0	35.0	11.4	122	64.6	227	63.6	622.7	5.133
0.422	31.60	40.50	21.3	7.61	81.0	41.5	143	43.4	409.9	3.379
0.562	22.60	25.20	14.3	5.17	48.7	26.4	89.2	32.1	263.7	2.174
0.750	13.85	16.50	9.60	3.04	31.4	16.2	63.4	24.1	177.9	1.468
1.000	8.77	10.85	5.78	1.91	19.25	11.85	43.8	19.10	121.3	1.000
1.33	5.96	7.49	3.64	1.20	14.8	7.46	32.8	19.10	87.7	0.723
1.78	4.12	4.66	2.25	0.92	9.25	5.92	27.1	19.10	73.3	0.604
2.37	2.54	3.08	1.68	0.59	7.12	4.62	27.1	19.10	65.8	0.542
3.16	1.58	2.25	1.10	0.44	5.78	4.62	27.1	19.10	62.0	0.511
4.22	1.50	1.54	0.87	0.38	5.78	4.62	27.1	19.10	60.9	0.502

Table 13
Variation of Copper Loss with System Voltage for AC Systems on the WF-2, F4J, and EA6B Aircraft Combined

System Voltage V_s (Per Unit)	Copper Loss (lb) for the Gage Sizes Indicated								Total Losses (Arbitrary Units)	Total Losses (Per Unit)
	8	10	12	14	16	18	20	22		
0.237	24.00	30.90	11.30	3.63	37.00	25.70	101.0	78.00	311.5	2.57
0.316	21.40	19.80	9.94	3.38	30.80	21.70	89.3	75.00	271.3	2.24
0.422	13.95	17.00	9.14	2.81	25.80	19.65	81.5	56.30	226.2	1.86
0.562	11.00	15.60	7.63	2.23	24.30	17.30	71.4	42.80	192.3	1.59
0.750	10.3	13.20	6.24	2.12	21.40	15.50	56.5	28.40	153.7	1.27
1.00	8.77	10.85	5.78	1.91	19.25	11.85	43.8	19.10	121.3	1.00
1.33	7.45	9.22	5.25	1.70	14.05	10.65	34.6	10.74	93.7	0.77
1.78	6.40	8.35	4.73	1.28	12.75	7.93	22.4	6.04	69.9	0.58
2.37	6.70	7.60	3.58	1.09	9.90	5.33	12.7	3.40	50.3	0.41
3.16	5.17	5.96	3.00	0.88	6.35	3.08	7.00	1.91	33.0	0.28
4.22	4.03	5.10	2.37	0.55	3.66	1.66	3.94	1.07	22.4	0.18

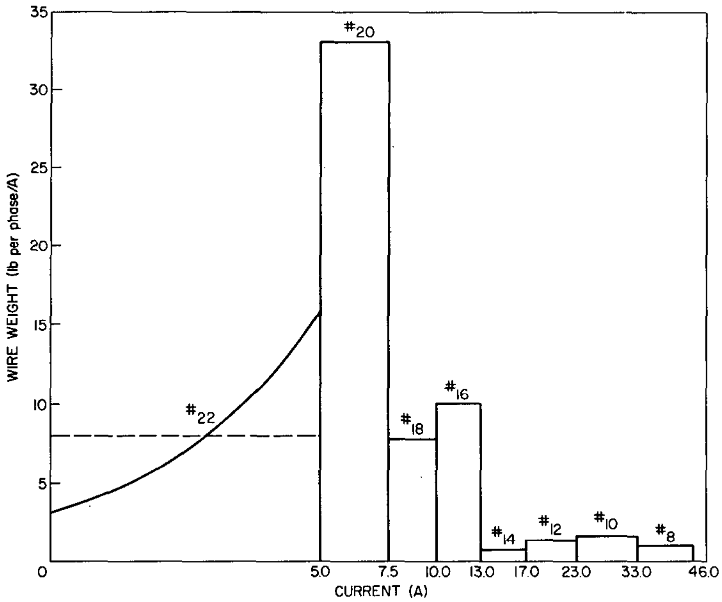

Fig. 7 - Per phase wire weight as a function of current for the indicated gage size wires used on the WF-2, F4J, and EA6B aircraft

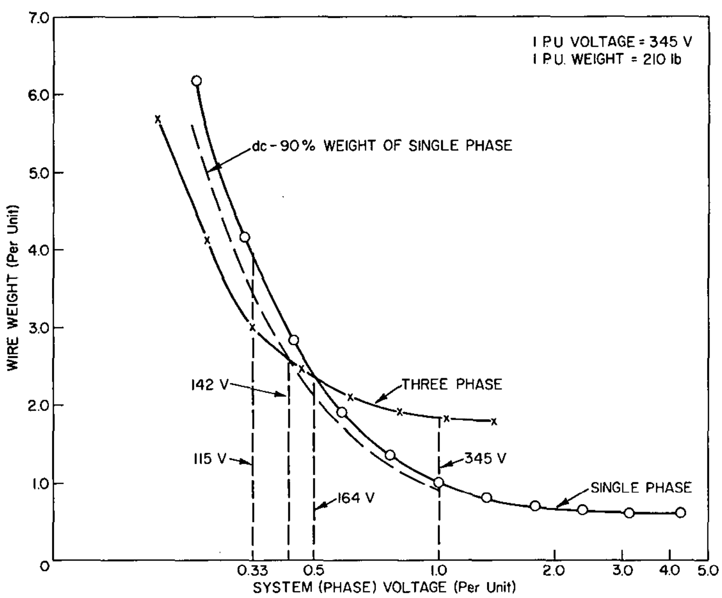

Fig. 8 - Comparison of wire weight of the present three-phase system with a single-phase or dc system (data from Table 11)

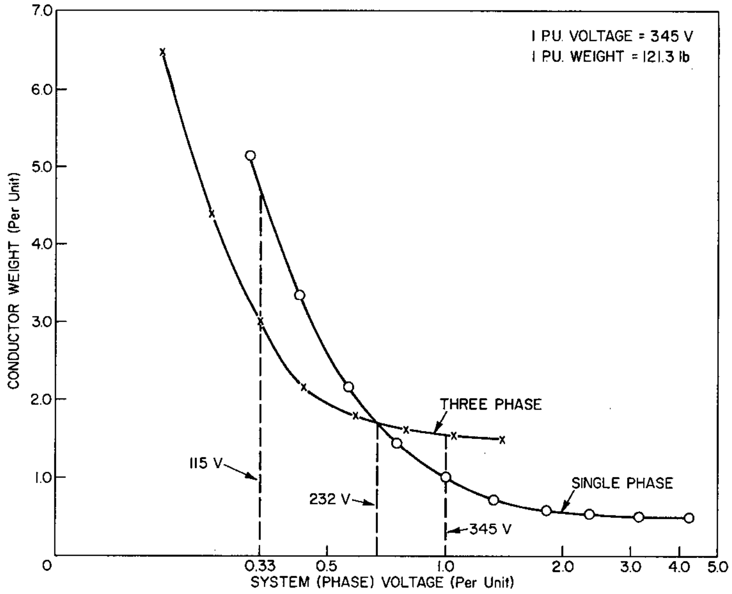

Fig. 9 - Comparison of copper weight of present three-phase system with single-phase or dc system as a function of system voltage (data from Table 12)

Table 14
Per Phase (or DC) Systems Wiring Weight, Systems Copper Weight, Systems Losses, and Wiring Weight Divided by Losses for the WF-2, F4J, and EA6B Aircraft Combined

System Voltage V_s (Per Unit)	Systems Wiring Wt. W'_{ws} (Per Unit)	Systems Copper Wt. W'_{ws} (Per Unit)	Systems Losses (Per Unit)	Av. Wire Wt. Per A-ft $W'_{ws} V_s$ (Per Unit)	Av. Copper Wt. Per A-ft $W'_{cs} V_s$ (Per Unit)	Systems Wire Wt. Divided by Losses
0.237	6.17	7.80	2.57	1.460	1.85	2.39
0.316	4.16	5.13	2.24	1.315	1.62	1.86
0.422	2.85	3.38	1.86	1.200	1.43	1.53
0.562	1.90	2.17	1.59	1.070	1.22	1.19
0.750	1.37	1.47	1.27	1.026	1.10	1.08
1.000	1.00	1.00	1.00	1.000	1.00	1.00
1.33	0.81	0.72	0.77	1.08	0.96	1.05
1.78	0.69	0.60	0.58	1.23	1.07	1.19
2.37	0.64	0.54	0.41	1.52	1.28	1.56
3.16	0.61	0.51	0.28	1.93	1.61	2.18
4.22	0.60	0.50	0.18	2.53	2.11	3.34

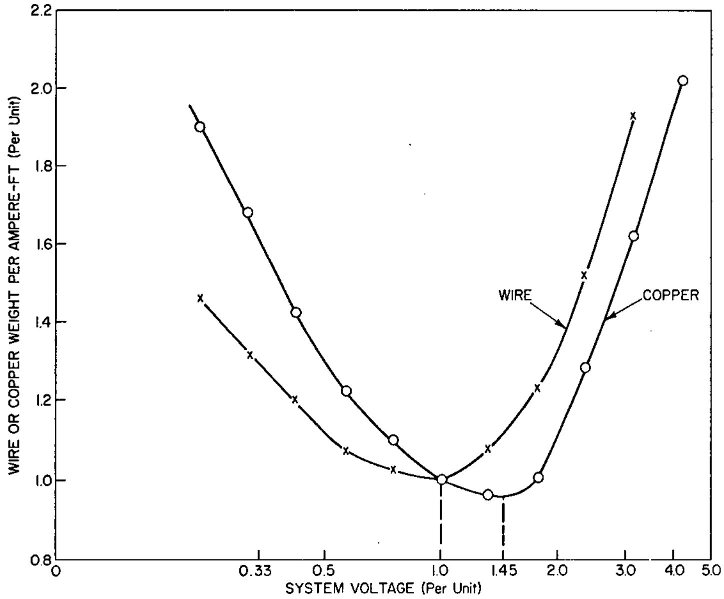

Fig. 10 - Variation of system wire weight and system copper weight as a function of system voltage (data included in Table 14)

is obtained by multiplying the wiring weight by the system voltage. The average wiring weight per ampere-ft, and the average copper weight per ampere-ft, are indicated in Table 14 and the values are plotted in Fig. 10. The minimum weight of wire per ampere-ft occurs at 1 P.U. voltage (see Fig. 10). This would be at 345 V for a single-phase system, or 115 V for a three-phase system. Hence, if the criterion of minimum average wire weight per ampere-ft is used, the present three-phase ac system is now at the point of optimum system voltage. If the copper weight per ampere-ft is taken as the criterion, then the present system voltage can be increased up to 1.45 times its present value, or 161 V. As the weight of insulation is always present, the use of the conductor weight alone is only a limiting condition.

In the interest of simplicity it is desirable that there be only one reference point for the establishment of the optimum system voltage. In using the criterion of minimum wire weight per ampere-ft, or minimum conductor weight per ampere-ft, no account has been taken of the system losses. In a conductor where the current density is highest, the I^2R loss is greatest per unit conductor weight. Figure 3 shows that wire gage size Nos. 16, 18, 20, and 22 near its maximum current rating, are the lightest wires per ampere-ft, yet the relative weight of insulation on these wires is greater than on the larger size wires. This is the result of higher current density and greater loss per unit weight in the smaller size wires. In view of this, the point in system voltage where the total wiring weight divided by the total I^2R losses is a minimum may be the best criterion for the establishment of optimum system voltage.

Systems wiring weight divided by systems I^2R losses, for the three aircraft used in this study, are shown in Table 14 and the results are plotted in Fig. 11. The minimum ratio occurs at a systems voltage of 1.00 P.U. As may be observed in Fig. 11, the ratio does not vary much between a systems voltage level of 0.5 and 2.00 P.U. The point to be emphasized is that, for every load on a system, both the weight and the losses decrease with increase in system voltage, but not equally. At all values of system voltage to the left of 1 P.U. in Fig. 11, the system weight is decreasing more than the reciprocal of system voltage, and at all points to the right of 1 P.U. the losses are decreasing more than

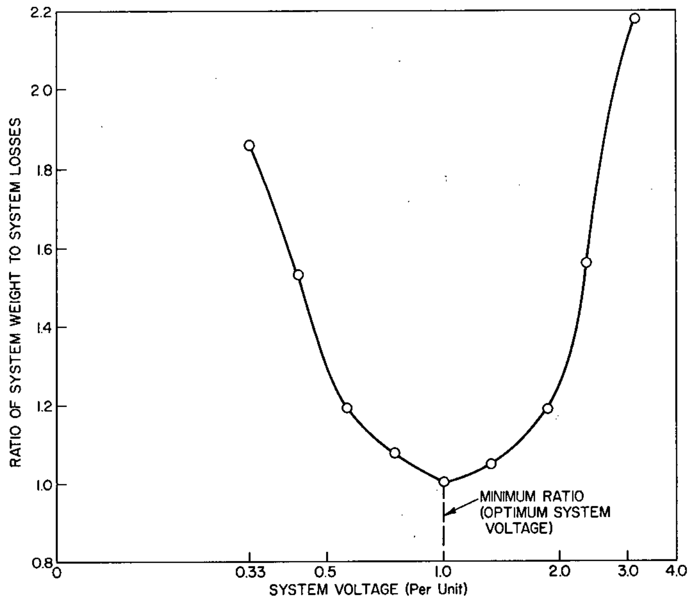

Fig. 11 - Ratio of system wire weight to system I^2R losses as a function of system voltage (data included in Table 14)

the reciprocal of system voltage. The 1 P.U. value of system voltage occurs at the point where both the total system losses and the total system weight vary inversely as the system voltage. It is the point of maximum conductor utilization and minimum wire weight and results in an "optimum" system voltage that falls between that of minimum wire weight per ampere-ft and minimum copper weight per ampere-ft (see Fig. 10).

CONCLUSIONS AND DISCUSSION

The final criterion for optimum system voltage has been arrived at by consideration of wiring weight and wiring losses only. Actually, many other factors, such as corona, insulation, magnitude of switching transients, design of protective devices, electromagnetic interference, acoustic noise, adaptation of utilization equipment to a new voltage level, and the weight and efficiency of voltage transforming equipment, should be considered not only in regard to system voltage level but also as to whether dc or ac would be most advantageous. Often, it is profitable to make some weight sacrifice or suffer a decrease in efficiency to obtain greater reliability or a decrease in maintenance requirements. A quantitive evaluation and weighing of all factors is not possible, but this does not negate nor lessen the usefulness of those factors which may be determined. Using system wiring weight and system wiring losses, a practical limit for optimum system voltage is obtained which insures that maximum load is carried by minimum size wires. Because of the many factors involved, the actual system voltage will generally be different from that arrived at by a consideration of weight and losses in the wiring system alone. However, the present three-phase system is optimum at the 115-V level, and this voltage level corresponds to 345 V for a single-phase or dc system. If, then, the effect of power factor and lower resistance for a dc system are considered, the optimum dc system voltage would be lower than that for the corresponding single-phase system. A plot of estimated dc wiring weight was shown in Fig. 8. This plot was obtained by estimating the dc system wiring weight to be 90% of the corresponding single-phase wiring weight. The crossover point with the three-phase curve is at 142 V. This indicates that, up to 142 V, the wiring weight savings that may be obtained is greater for the three-phase system than for a dc (single-phase) system at the same voltage. It is definitely indicated that a dc system at 115 V would not show any wiring weight savings over the present three-phase system, and it is concluded that the minimum voltage for a dc system, in order to show some wiring weight advantage over that to be obtained by increasing the voltage level of the present ac system, is above 150 V. If the present ac system voltage is increased from 115 to 150 V, the wiring weight would decrease to about 85% of present value. Above 150 V a dc system (so far as savings in transmission wire weight is considered important) is superior to a three-phase ac system at the same voltage.

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13. ABSTRACT

A method for computing the wiring weight, conductor weight, and conductor losses as a function of system voltage is described for aircraft electrical power systems.

It is indicated that if phase voltage at the load is considered as system voltage for single-phase ground return systems and multiphase grounded neutral systems, then the number of wire conductors is equal to the number of phases. Hence, wiring weight, I^2R losses, and the number of conductors are directly proportional to the number of phases in a system and, for the same loads, the system voltage is inversely proportional to the number of phases. A 345-volt (three times the present 115-volt, three-phase voltage) single-phase system voltage would reduce the wiring weight, copper losses, and number of conductors to one-third their present value (on the three-phase ac system).

A significant point, or criterion, for optimum system voltage is reached at a system voltage where the system wiring weight divided by system wiring losses is a minimum.

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Aircraft						
Electric power transmission						
Electric wire						
Wiring						
Electrical potential						
Wire weight						
Gage number						
Alternating current						
Direct current						
Three-phase systems						
Single-phase (dc) systems						